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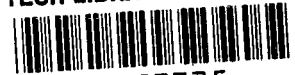
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*by Marcus F. Heidmann*

*Lewis Research Center*

*Cleveland, Ohio*



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# OXYGEN-JET BEHAVIOR DURING COMBUSTION INSTABILITY IN A TWO-DIMENSIONAL COMBUSTOR\*

by Marcus F. Heidmann

Lewis Research Center

## SUMMARY

A burning liquid-oxygen jet was observed photographically during both stable and unstable operation in a gaseous-hydrogen-fueled rocket combustor. The stable jet appeared as a loosely contained mass of liquid, which disintegrated into a maze of interconnected ligaments. Normal drop formation was not observed. During chugging instability, the oxygen flow rate responded to chamber-pressure oscillations and caused large variations in the atomization process. The burning rate appeared to respond to both the degree of atomization and the quantity of liquid within the combustor. Cyclic variations in the magnitude and the position of the primary burning zone were evident. With high-frequency transverse instability, the length of the burning jet decreased from its stable value and responded to the oscillations. No abrupt change in jet characteristics was evident during the cyclic process. Mass removal appeared as a continuous process depending on the gas velocity and the amount of liquid subjected to this velocity.

## INTRODUCTION

The atomization and burning of noncryogenic liquids have been extensively studied in a variety of environments. A basic understanding has evolved which, for many conditions, adequately describes the combustion process. A similar knowledge about liquid oxygen and other cryogenic liquids does not exist. Nonburning studies of the atomization process of liquid oxygen are incomplete and the extrapolation of noncryogenic liquid spray data may be inadequate because of large and uncertain differences in physical properties. One of the purposes of this study was to obtain a general physical descrip-

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tion of a burning liquid-oxygen jet during stable combustion to define unique characteristics requiring more extensive study.

With regard to unstable combustion, the injection and atomization processes are only partly understood for all liquids. The dynamic behavior of injection processes has been studied in shock tubes, resonant cavities, pulsed liquid flow systems, and other devices that produce unstable combustor conditions. Substantial effects on the atomization process have been observed, and a degree of understanding is evolving. Most of the experimental techniques involve nonburning sprays. The dynamic behavior in a burning spray is more complicated because mass is continually being removed by vaporization, mixing, and chemical reaction. This mass removal process can also respond to rapidly changing environmental conditions. The net effect of periodicity in the injection process with periodicity in the combustion or mass removal process remains to be evaluated. Its importance is implied in an instability analysis being conducted by R. J. Priem at the Lewis Research Center. A relation is evident between the liquid mass within the combustor and the growth of a disturbance. The net amount of liquid mass, the degree of cyclic variation in this liquid mass, and the phase relation to the disturbance may provide the criteria for stability. The analysis is for screaming instability; however, liquid mass within the combustor may be equally important for chugging instability. The primary purpose of this study was to observe an injection and combustion process during instability to confirm the existence of cyclic variations in atomization and other phenomena predicted from nonburning and theoretical studies.

The studies reported herein were made in a two-dimensional combustor that permitted detailed observations of the injection and burning process. Observations were made in the stable, chugging, and spinning transverse instability regions. Liquid-oxygen jets in a diffuse hydrogen atmosphere formed the basic injection and combustion pattern.

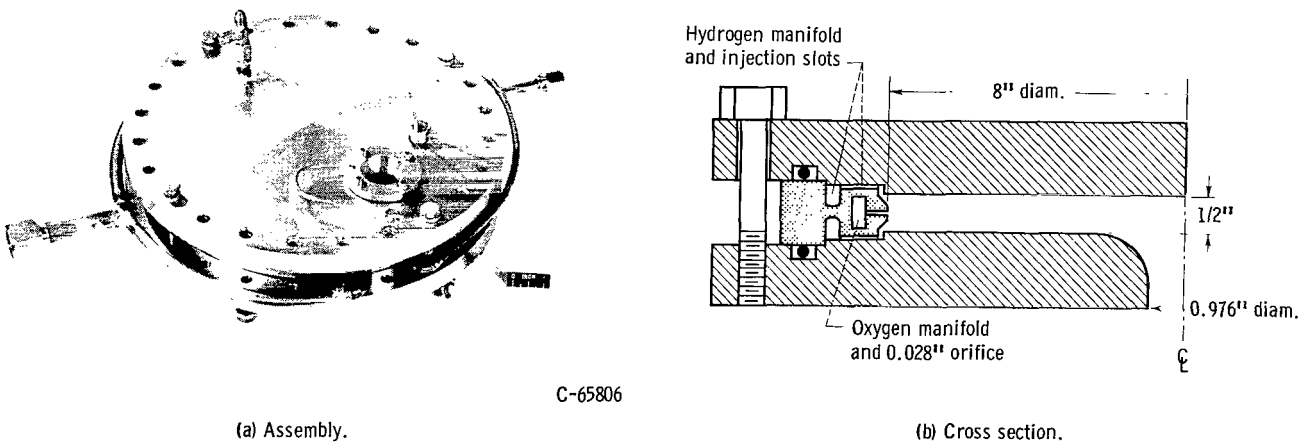


Figure 1. - Two-dimensional circular combustor.

## EXPERIMENTAL TECHNIQUE

A two-dimensional circular combustor was used (fig. 1). Basically, the combustor consists of a circular injector ring 8 inches in diameter and 1/2 inch thick with 48 oxygen jets that inject radially toward the center of the ring. (Gaseous hydrogen is introduced in a diffuse manner near the oxygen jets.) Both sides of the ring are covered with circular plates, one solid and the other with an exhaust port at its center. The 48 oxygen jets are 0.028 inch in diameter and are equally spaced around the circumference. Jet behavior was observed through 1-inch-diameter windows, which were centered on an individual oxygen jet.

Combustion tests were made with a pressurized liquid-oxygen tank and flow system that was cooled to liquid-nitrogen temperatures. A pressure-regulated gaseous-hydrogen supply system at ambient temperatures was used. Combustion pressure and oxygen and hydrogen flow rates were the primary parametric measurements for steady-state performance. A piezoelectric crystal transducer in a water-cooled holder was used for dynamic pressure measurements. The transducer was located immediately adjacent to the window to detect dynamic pressure conditions at the region of observation.

Transverse combustion instability was induced by tangentially injecting nitrogen gas through a 1/8-inch-diameter port into the combustor. The injection port was near the circumference of the combustor. Nitrogen flow rates of 0.029, 0.055, 0.112, and 0.222 pound per second were used to vary the degree of instability. The flow rate was established by interchangeable critical-flow orifice restrictors located in the flow line 10 orifice diameters upstream from the injection point. Nitrogen gas was injected for 0.3 to 0.4 second during a  $1\frac{1}{2}$ -second test firing.

Instability was induced by this technique in a similar two-dimensional combustor described in NASA Lewis Film C-226 entitled "Visualization studies of Combustion Instability in a Hydrogen-Oxygen Model Combustor," which is available on loan from the Lewis Research Center. (Requests should be directed to Chief, Technical Information Division (5-5), NASA, Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.) This film presents high-speed motion pictures of stable and unstable combustor operation as observed through a transparent top cover plate. Overall combustion and flow patterns are described for spinning transverse instability.

In the present study, high-speed motion pictures were taken through the 1-inch-diameter windows. A collimated light beam from a concentrated zirconium arc was passed through the combustor, and silhouette-type pictures were taken with tri-emulsion color film. A cutoff filter placed between the light source and the combustor passed red light above 5800 angstroms. The camera recorded a silhouette of the oxygen jet against a red background with blue light from the hydrogen and oxygen reaction superimposed on this background.

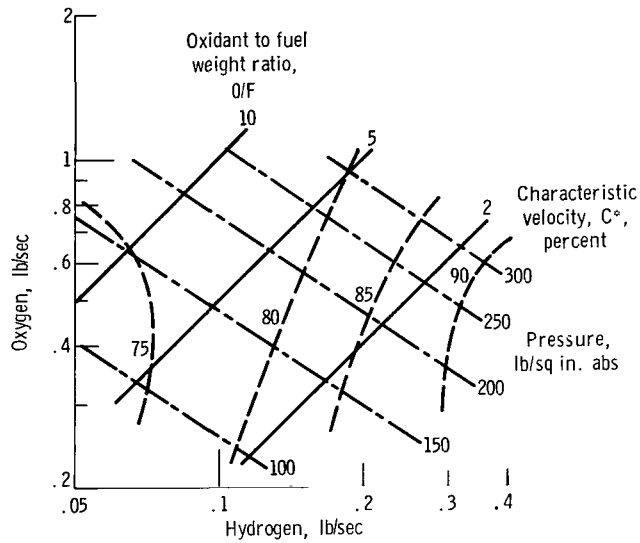


Figure 2 - Combustor performance.

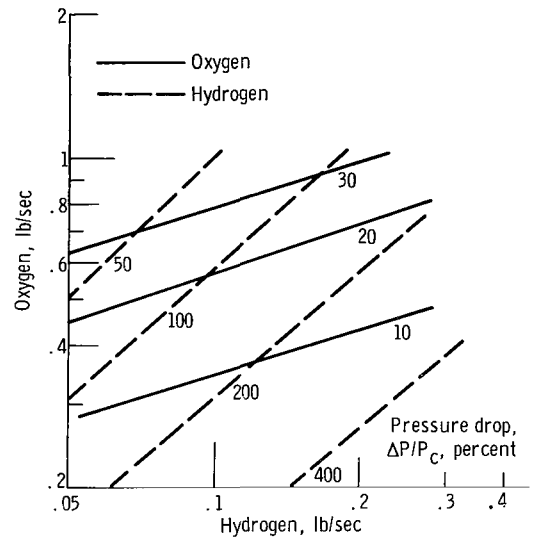


Figure 3. - Injection pressure drop in percent of combustor pressure.



Figure 4. - Typical oxygen jet with stable combustion.

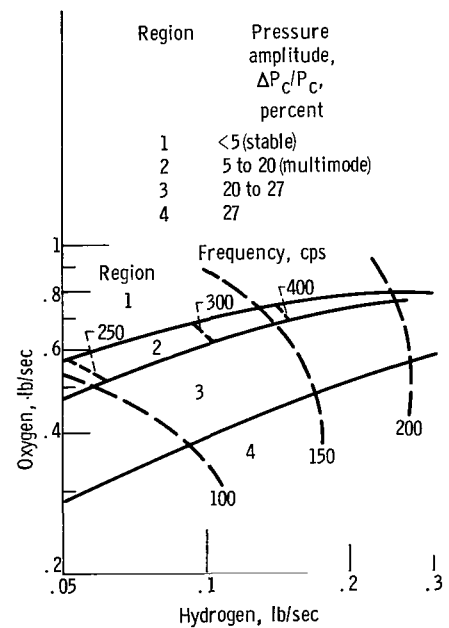


Figure 5. - Chugging instability.

## COMBUSTOR PERFORMANCE

The combustor performance over the operating range covered in this study is shown in figures 2 and 3. Characteristic velocity varied from 70 to 90 percent of theoretical. This indicated incomplete combustion throughout the operating range when nitrogen gas was not injected to induce instability. Injection pressure drop (fig. 3) was relatively high for hydrogen and low for oxygen. Oxygen pressure drop covered the range of interest in chugging instability, whereas hydrogen flow should have been relatively insensitive to chamber-pressure changes.

The burning oxygen jet for typical steady-state combustion is shown in figure 4. This is an enlargement of a single 16-millimeter frame of color film, which in a black-and-white print does not clearly show the burning zone. Analysis of such photographs shows that a luminous combustion zone uniformly enveloped the jet at the jet origin. The zone extended about 0.15 inch from the jet surface. The zone expanded and became turbulent downstream from the jet origin. The oxygen jet was loosely confined compared with water or hydrocarbon jets. The appearance during breakup was that of a maze of interconnected ligaments. Isolated liquid particles were irregular in shape, and typical drop formation was not observed within the limit of resolution, about 100 to 200 microns.

A low surface tension is implied by the jet appearance. Surface tension decreases with an increase in temperature. At the injection temperature surface tension is less than, but comparable to, that of the hydrocarbons. The temperature of the burning jet, however, is not known, and the surface tension may be reduced to extremely low values if combustion heat is transferred to the oxygen. A high vaporization rate and the proximity of the combustion zone may also affect surface properties. Additional studies appear necessary to describe oxygen atomization characteristics within the combustor.

## CHUGGING INSTABILITY

Self-induced chugging instability developed over a major portion of the combustion operating range. Figure 5 shows several characteristics of this instability. The amplitude of the pressure oscillation is divided into four regions, with region 1 defined as stable. The parameter that approximates the boundary between these regions is  $\Delta P/P_c$  of the oxygen (presented in fig. 3). A stable condition exists with  $\Delta P/P_c$  greater than about 0.25.

Two modes of oscillation were encountered: a fundamental chugging mode and a mode with a frequency about 2.7 times the fundamental mode. This higher frequency condition occurred randomly and only in region 2.

The four regions were separated on the basis of pressure amplitude; the primary

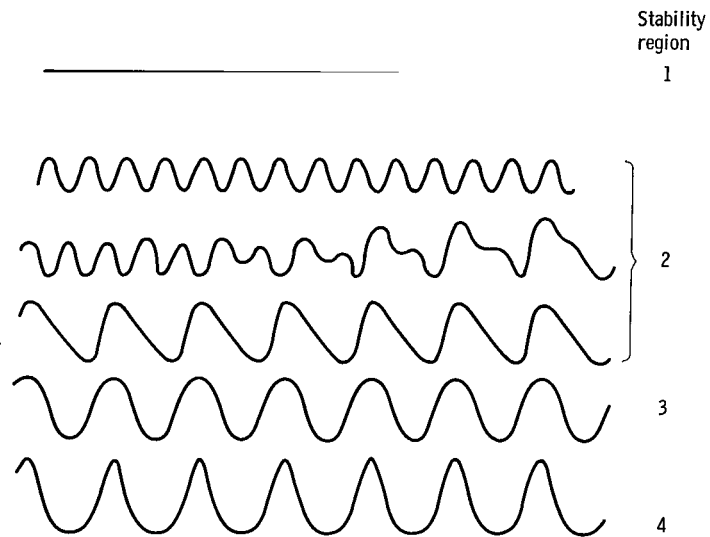


Figure 6. - Typical waveshape during chugging instability.

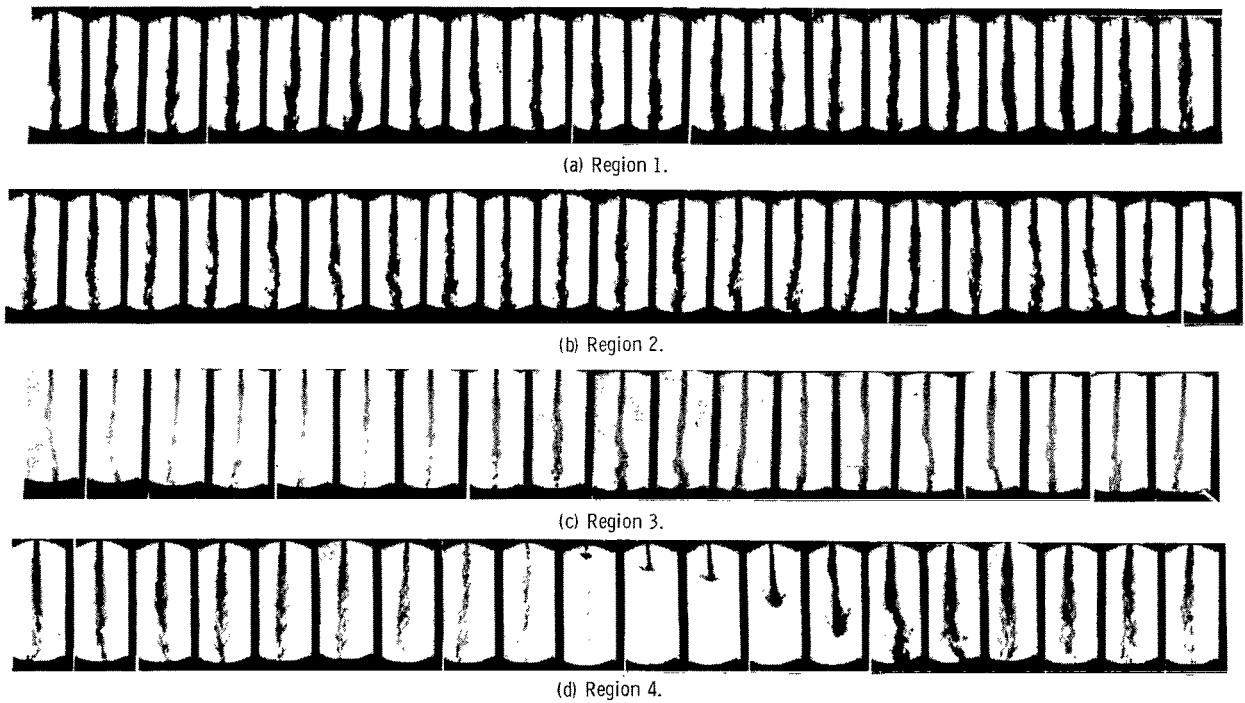


Figure 7. - Liquid-oxygen-jet behavior with chugging instability.

reason for this division was the waveshape (see fig. 6). The most severe oscillations occurred in region 4, and a cusp-shaped wave, characteristic of nonlinear effects, was obtained. A change in operating conditions toward a region of stability caused progressive changes in waveshape. A sinusoidal wave was evident in region 3, where the wave became steep-fronted in region 2 before stability was reached in region 1. An alternative condition in region 2 was a sinusoidal high-frequency and a mixed-mode waveshape. Such a progression in waveshape suggests a shifting of phase relation between the driving, driven, and resonant parts of the system.

The oxygen-jet characteristics in the four regions are shown in figure 7. An extreme oscillation in flow rate is evident for region 4 with almost complete termination of flow. A characteristic of such flow oscillations is the liquid "mushroom" that developed during flow acceleration. This mushroom was produced when high-velocity flow leaving the orifice impinged on lower velocity flow that had preceded it and caused a piling up of oxygen. The intensity of the flame radiation that surrounded the liquid oxygen oscillated depending on the amount of oxygen present and the degree of atomization or dispersion. The degree of atomization was obviously not constant. The injection and combustion process appears to have behaved nonlinearly, which may account for the shape of the pressure wave observed in this region.

Changes in liquid-jet characteristics were less severe in region 3 and became progressively more stable in region 2. In some instances, the oscillation in flame radiation, not shown in the figure, was more evident than changes in atomization. Flame-radiation changes, however, may indicate a combustion change caused by an oscillation in pressure or environmental conditions rather than atomization. The description of the oxygen jet in regions 2 and 3 is not complete because of the limited view through the observation ports. Downstream from the window, the jet may have had properties similar to those observed in region 1. Jet behavior during higher mode oscillations were not isolated because of the random occurrence of this instability.

These observations indicate that the atomization of liquid oxygen during chugging may exhibit nonlinear behavior. This causes the combustion zone to oscillate in intensity and position. Such oscillations may be more severe for a combustion process controlled by oxygen injection and atomization than by injection and atomization of other liquids. The loosely bound property of oxygen jets and ligaments makes it particularly sensitive to perturbations in flow rate and combustor conditions.

## SPINNING TRANSVERSE INSTABILITY

The modes of transverse instability induced by nitrogen flow are shown in figure 8. Sustained oscillations was the criterion separating stable and unstable regions regard-

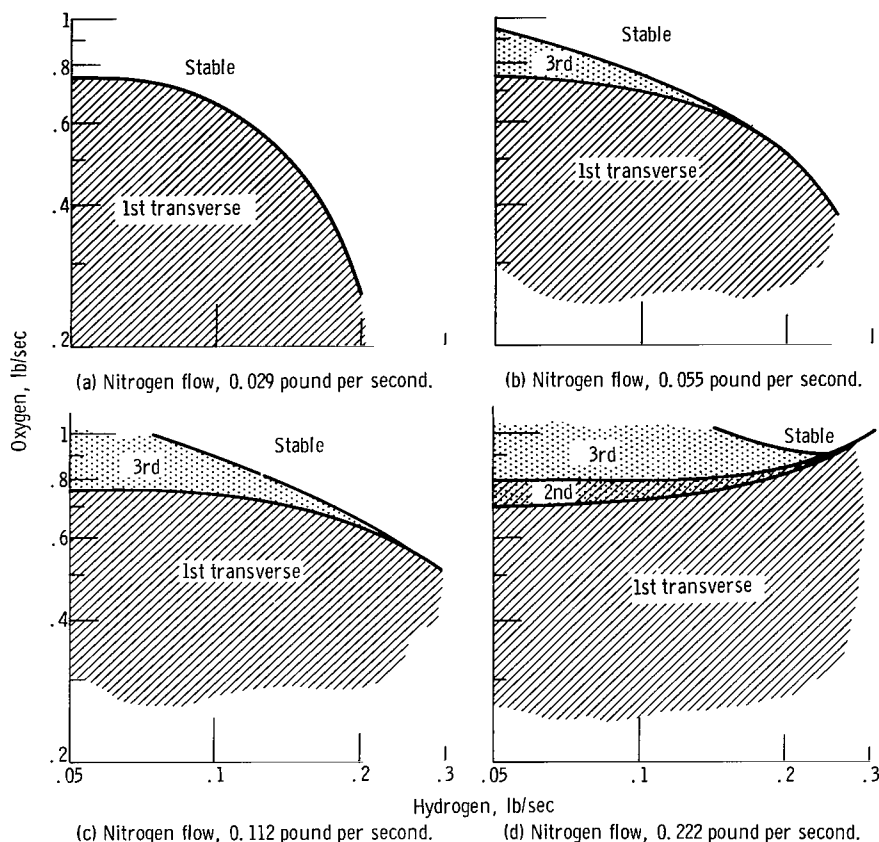


Figure 8. - Transverse instability regions.

less of the wave amplitude. The boundaries separating stability regions are approximate and are shown primarily to indicate trends. The first transverse mode was identified as spinning rather than standing by simultaneous observations at several positions in the combustor.

A comparison of the four stability maps in figure 8 shows the effect of nitrogen flow rate on inducing instability. As the nitrogen flow rate increased, the unstable operating region expanded. The amplitude of the oscillation also increased and was approximately proportional to the increase in nitrogen flow. It is interesting to note that the third harmonic occurred prior to the second as the instability region expanded. Combined chugging and transverse instability occurred at low oxygen flow rates. With nitrogen flow the chugging region was less extensive and oscillation exhibited a higher frequency than in the case with no nitrogen flow.

A circular flow was induced by the injection of nitrogen gas, which changed the normal burning process and produced conditions conducive to sustaining combustion instability. Several tests with hydrogen rather than nitrogen injection indicated that the momentum of the injected gas establishes the degree of instability. Inertia and other forces resisting circular flow would be assumed to be controlling parameters. A constant tangen-

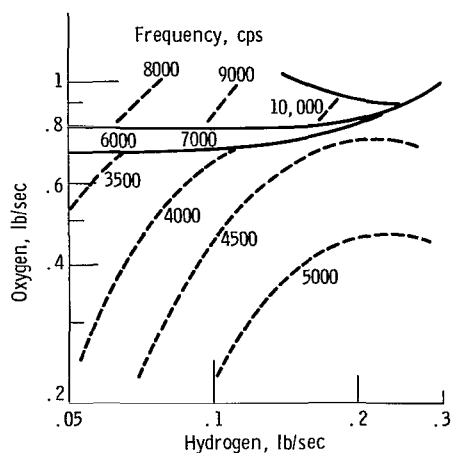


Figure 9. - Frequency of transverse instability with 0.222-pound-per-second nitrogen flow.

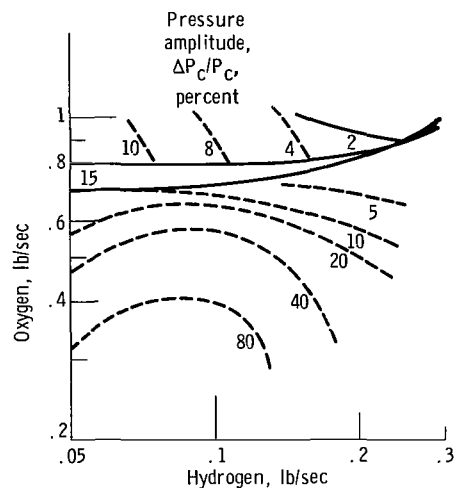


Figure 10. - Amplitude of transverse instability with 0.222-pound-per-second nitrogen flow.

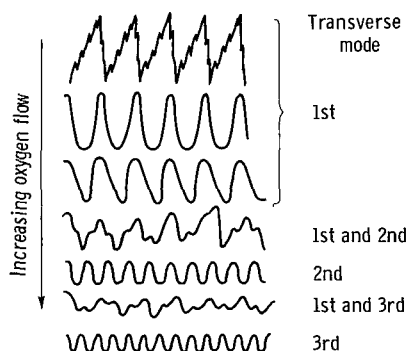


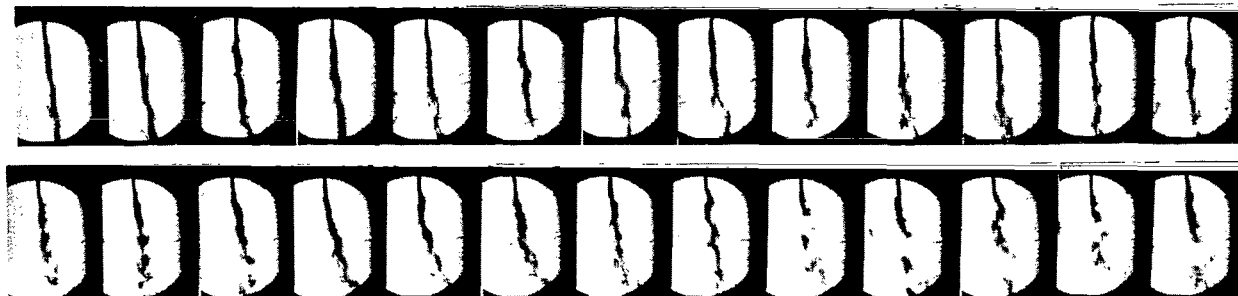
Figure 11. - Combustor pressure wavelike at constant hydrogen and nitrogen flow rates.

tial flow rate would be most effective in inducing circular flow at low propellant flow rates. The stability maps appear to reflect this condition, since low nitrogen flow rates induced instability at low propellant flow rates.

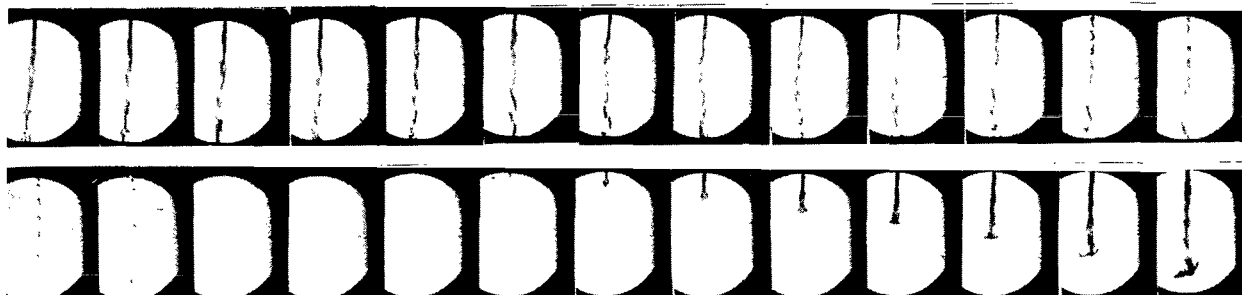
The frequency and pressure amplitude of the oscillation for the highest nitrogen flow condition are shown in figures 9 and 10. The frequencies compare very closely with those of a 100-percent-efficient combustor, although they were somewhat less at lower nitrogen flow rates. A direct comparison with performance efficiency was not made because combustor pressure was measured near the circumference, and the added pressure drop due to circular or vortex flow increased the pressure needed for performance evaluations by an unknown amount. The amplitude shown in figure 10 is approximate because of uncertainties caused by waveshape and transducer response; however, a transducer calibration showed linear response to pressure to within  $\pm 10$  percent for frequencies up to 10,000 cps.

As operating conditions were changed toward a region of stability, a progressive change in the waveshape of the pressure oscillations was observed. The general nature of the waveshape progression is shown in figure 11, although additional variations were also detected. Waveshape progression was somewhat similar to that observed with chugging instability, that is, steep-fronted waves to higher modes to stable combustion. Again, a time response that affects amplitude, frequency, and waveshape of the oscillation is implied.

The progression observed in waveshape also implies that one form of stable combustion may result from a highly responsive process that drives an extremely high frequency at low amplitude. Pressure records in the stable region with



(a) Typical transition.



(b) Transition for low oxygen pressure drop.

Figure 12. - Transition from stable to screaming combustion.



(a) Pressure amplitude,  $\Delta P_C/P_C > 40$  percent; low oxygen jet velocity



(b) Pressure amplitude,  $\Delta P_C/P_C$ , 20 to 40 percent.



(c) Pressure amplitude,  $\Delta P_C/P_C$ , 10 to 20 percent.



(d) Pressure amplitude,  $\Delta P_C/P_C < 10$  percent; high oxygen jet velocity.

Figure 13. - Liquid-oxygen-jet behavior with first transverse mode of instability.

high nitrogen flow rates contained high-frequency noise, whereas a smooth record existed without nitrogen flow. These two stable conditions may have been stable for separate reasons. The theoretical analysis by Priem shows that stability can exist with low and extremely high burning rates; instability occurs at some intermediate burning rate. Stability with and without nitrogen flow may be of these two types.

High-speed motion pictures of the jet during the transition from stable to unstable combustion are shown in figure 12(a). The tangential velocity caused by the nitrogen flow accelerated the combustion process and reduced the length of the oxygen jet. Study of such photographs together with pressure records indicate that the nitrogen flow established a new level of combustion rate followed by the growth of an oscillation. The nitrogen flow established a condition conducive to instability rather than pulsed the combustor into an unstable condition.

The transition from stable to unstable in a region of strong chugging instability differed in character, as shown in figure 12(b). Combustion pressure was increased by nitrogen addition and accelerated burning. Oxygen flow rate reacted to the pressure change and terminated for a short period of time. The oscillation persisted through a period when there was no burning.

Jet behavior during transverse instability of the first mode is shown in figure 13. These photographs time-resolve jet behavior during wave motion by a stroboscopic effect. Successive photographs display conditions in successive oscillations. The photographs, however, were taken at an advancing phase relation with respect to the oscillation. One to two cycles are displayed by this technique in figure 13.

Figure 13(a) shows jet behavior during high-amplitude oscillations. The average jet length was about  $1/4$  inch; however, this length varied during the oscillation. Precise tracking of the jet length is difficult because of the stroboscopic technique. Jet characteristics were not precisely repeated for each cycle, and detail changes have not been time-resolved. The varying jet length indicates that liquid mass within the combustor varied periodically, which agrees with analytical deductions.

Cyclic variations in gas velocity appear to have caused the variations in jet length. The velocity effect was most pronounced at the leading edge of the jet, but it was not abrupt. It appears to have persisted at varying degrees throughout the cycle. Loosely confined oxygen was displaced or stripped from the main body and rapidly disappeared because of vaporization and burning.

Figures 13(b) to (d) show jet behavior at progressively less severe oscillatory conditions. Average jet length increased, and the mass removal process became less severe. Shattering of the main column of the jet was not observed under any conditions, however, shattering of ligaments may have occurred. Stripping of liquid from the main body appears as a more important factor than effects caused by internal excitation within the liquid.

## SUMMARY OF RESULTS

A study of the behavior of liquid-oxygen jets in relation to combustor-performance characteristics gave the following results:

With stable combustion, a loosely confined jet was formed which disintegrated into a maze of interconnecting ligaments. Combustion radiation surrounded the jet and the ligaments. Normal drop formation was not observed.

Chugging instability was characterized by progressive changes in the waveshape, frequency, and amplitude of the pressure oscillations. The pressure oscillations caused pronounced changes in the oxygen flow rate and the degree of atomization. Combustion radiation varied in position and magnitude depending on the degree of atomization and the amount of liquid in the combustor. A complex interaction of parameters is implied.

Screaming instability, with a spinning transverse mode predominating, was induced by tangentially injected nitrogen gas. Waveshape, frequency, and amplitude of the pressure oscillations showed progressive changes that indicated a variable response time of interacting parameters. The average length of the oxygen jet decreased during screaming. The jet length varied periodically with the oscillation; however, no abrupt changes in atomization were observed. Oxygen appeared to be continuously stripped from the main bulk of the jet by the varying gas velocity that accompanied the oscillation. The process varied with the amplitude of the oscillation.

## CONCLUDING REMARKS

A unique characteristic of the burning liquid-oxygen jets observed in this study was the loosely confined nature of the jet. A more quantitative evaluation of this jet structure and breakup process is needed before the steady-state burning process of liquid oxygen and hydrogen can be fully described. This jet property also appears to make the burning process particularly sensitive to flow rate and combustor environment changes encountered during combustion instability. Jet behavior during instability appears to be an important interacting process, as was anticipated from analytical studies. Only a general physical description of the behavior was obtained, whereas specific knowledge of changes in the atomization and mass-removal process is needed. The phase relation between jet behavior and various combustor parameters is also needed to proceed in the evaluation of analytical models of combustion instability. The ability to observe the behavior of the burning jet makes this combustor applicable to further studies of this type.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, November 3, 1964.

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